Azimuthal correlations in p+p/A & relations to nucleon structure

Soeren Schlichting

Based on work in collaboration with:
Dusling, Lappi, Schenke, Tribedy, Venugopalan

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UNIVERSITY of WASHINGTON

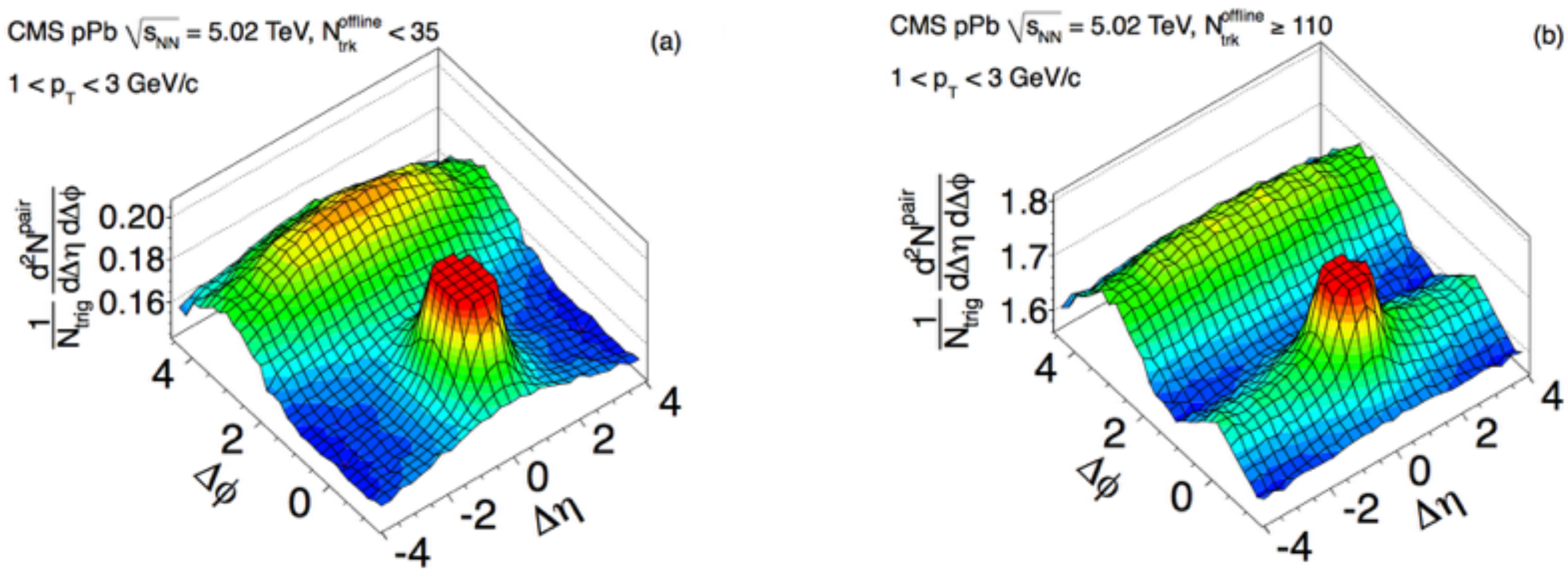
Outline

- Experimental results on high-multiplicity p+p/A
- Explanation 1: Collective response to initial state geometry?
  - Hydrodynamics in p+p/A
  - Event-by-event geometry and proton “shape”
- Explanation 2: Initial state momentum correlations at small-x?
  - Qualitative picture of correlations
  - State of the art & challenges in calculations
- Challenges & perspectives

Reviews: Dusling,Li, Schenke, Int.J.Mod.Phys. E25 (2016) no.01, 1630002
Schlichting, Tribedy, Adv. High Energy Phys. Vol. 2016 (2016), 8460349

Long-range azimuthal correlations

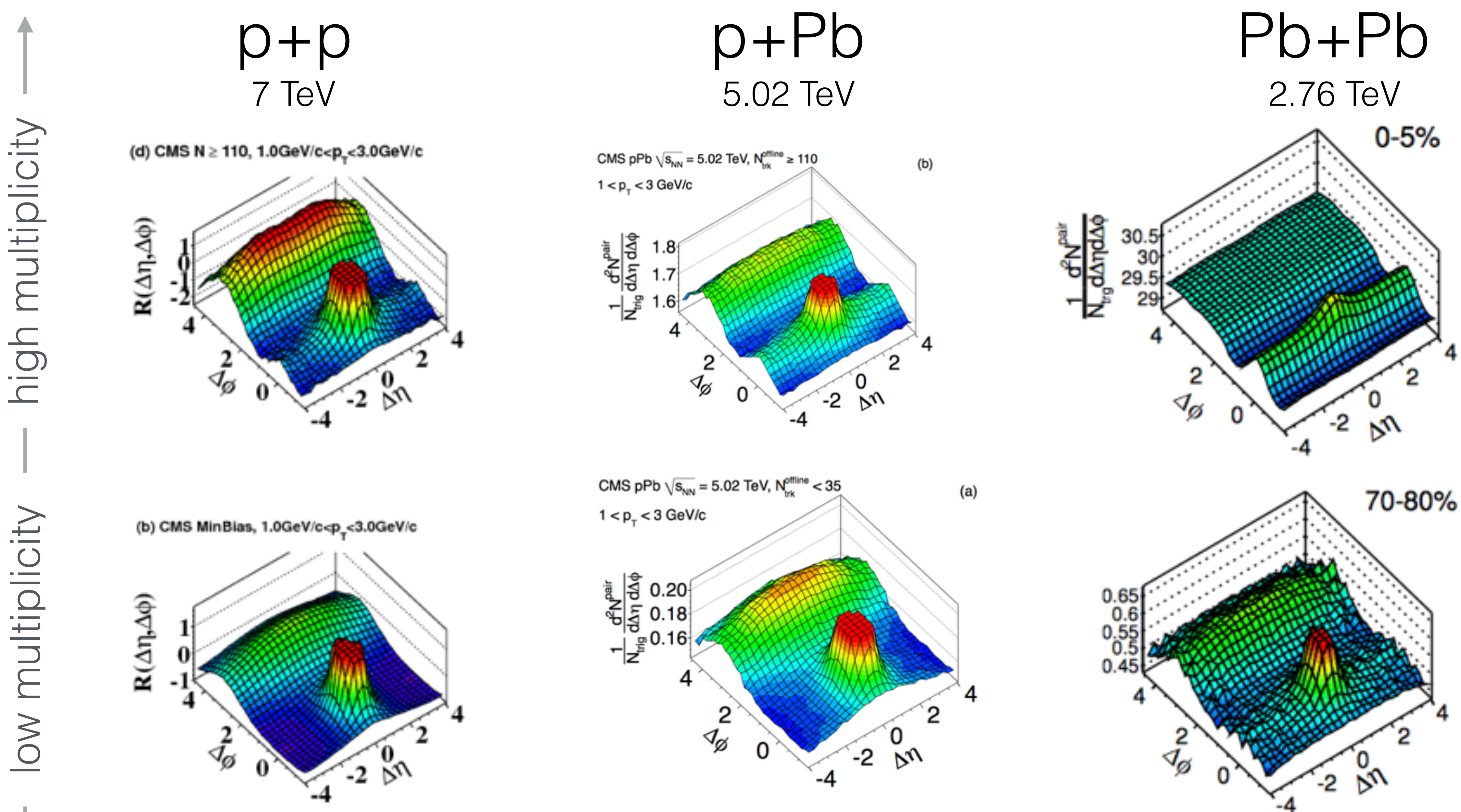
Experimentally long-range azimuthal di-hadron correlations have been observed in high multiplicity p+p/A at LHC as well as p/d/He3+A collisions at RHIC



low multiplicity —— high multiplicity →

Big surprise: No natural explanation of near-side ridge in pQCD

Long-range azimuthal correlations



Surprising similarities as conventionally p+p/A provide background measurements for A+A

Long-range azimuthal correlations

Even though many features of near-side ride in p+p/A are similar to observations in A+A collisions, there are also important differences

-> in p+p/A only observed in (rare) high-multiplicity events

-> so far no observation of jet-quenching in p+p/A

Different theoretical explanations developed in terms of

collective response to initial state geometry

and/or

initial state momentum correlations

Nature of high-multiplicity p+p/A events

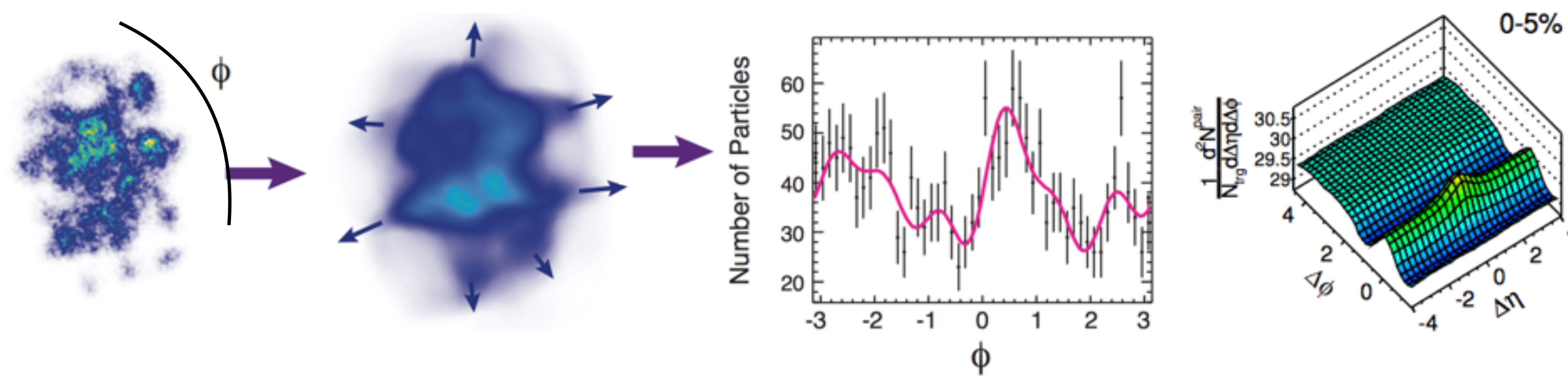
High-multiplicity events exhibit exceptionally large parton densities in the initial state

If parton densities in high-multiplicity events are sufficiently large, interaction between produced parsons can be significant

-> Creation of small droplet of QGP?
Space-time dynamics similar to A+A collision?

Hydrodynamic description of QGP in A+A collisions

Initial state | Hydrodynamic expansion | Azimuthal anisotropy | Statistical average

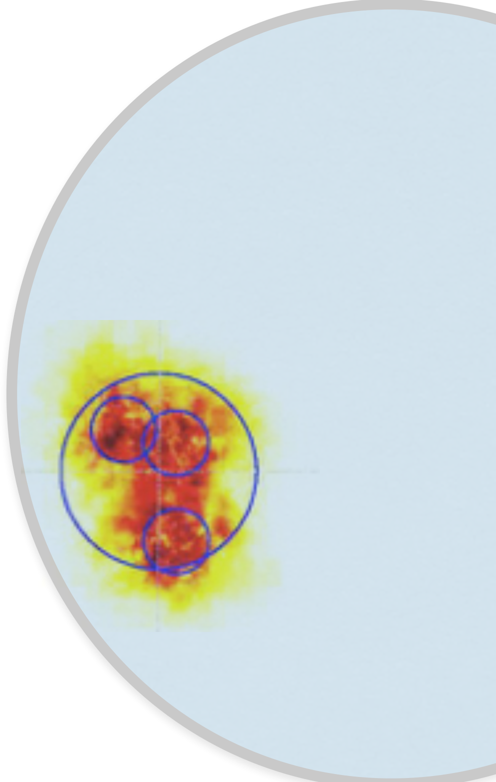


Hydrodynamic expansion converts initial state eccentricity to final state momentum space anisotropy of particle spectra

Event-by-event anisotropy reflected in correlations:

$$\frac{d^2N}{d\eta d\Delta\phi} = \left\langle \frac{dN}{d\Delta\eta_1 d\phi_1} \frac{dN}{d\eta_2 \Delta d\phi_2} \right\rangle$$

Hydrodynamics description of p+p/A collisions



Generating azimuthal correlations as a response to initial state geometry requires a non-trivial event geometry

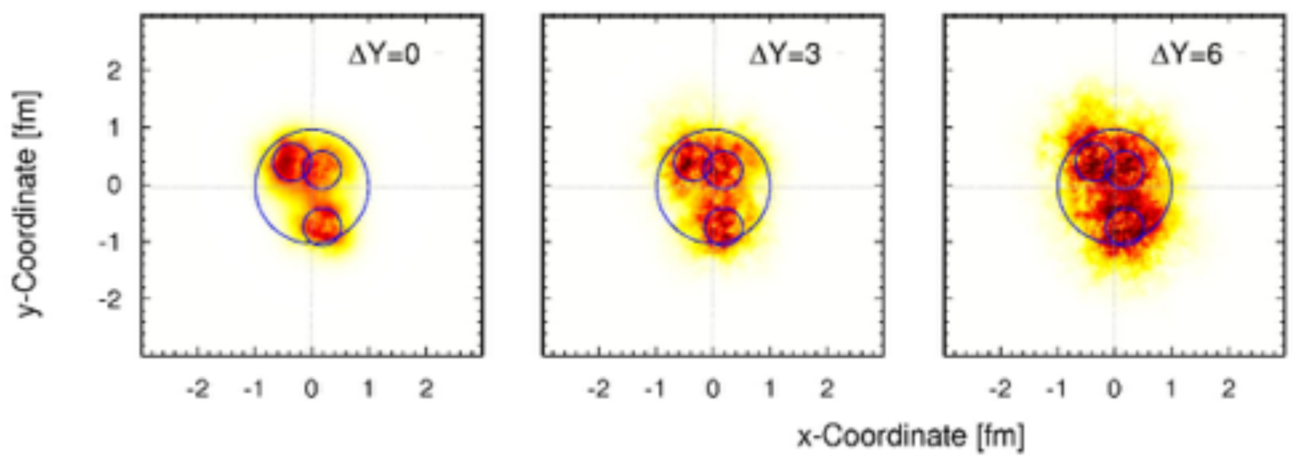
Event geometry in p+p/A collisions closely reflects b-dependence of gluon distribution in proton

Schenke, Venugopalan PRL 113 (2014) 102301

-> event-by-event fluctuation of the proton necessary to generate sizable anisotropies

Single event different from inclusive averages probed e.g. in GPD's

(c.f. talk by B. Schenke)

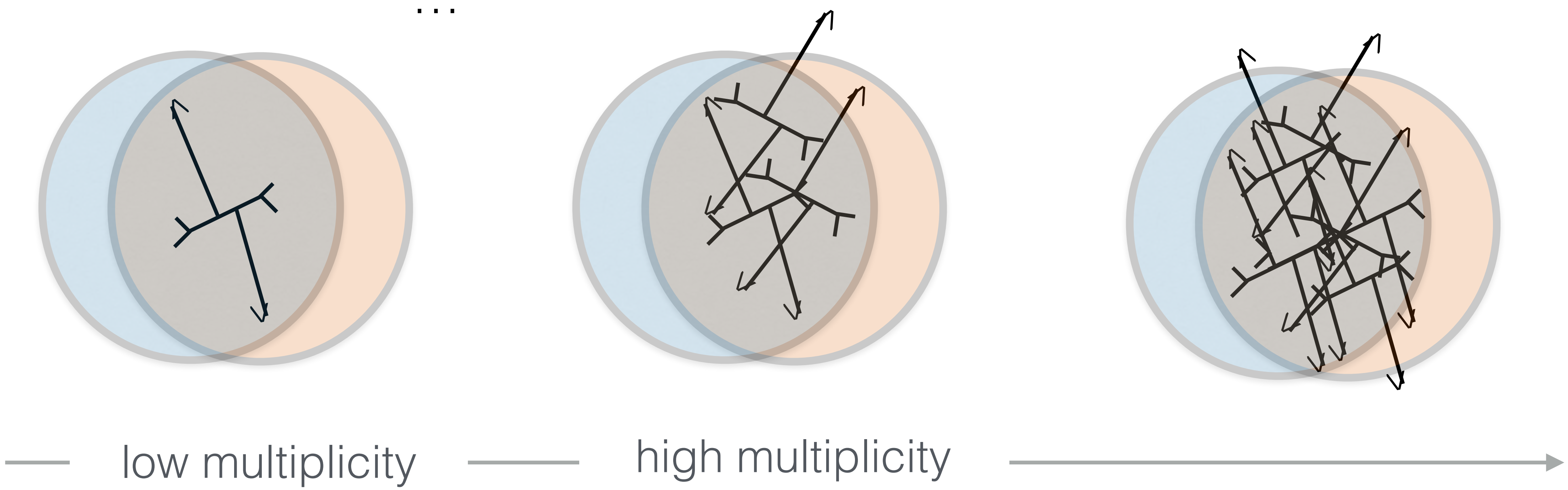


SS, Schenke B739 (2014) 313-319

Hydrodynamics in p+p/A?

Several models of “eccentric” protons emerging, which can be tuned to obtain decent description of data

Several challenges: Validity of hydrodynamics for small systems?
Strongly interacting QGP vs. no jet-quenching?
…

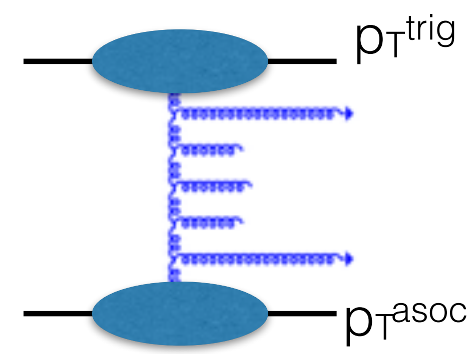


Even though final state effects will eventually dominate at very high multiplicity, it is also possible that this point simply has not been reached in present RHIC and LHC experiments

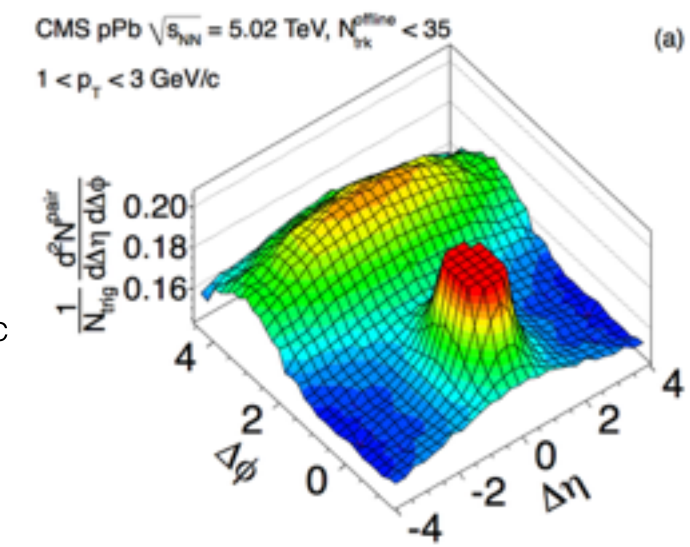
-> Observed correlations could reflect modification of initial state correlations in regime of high parton densities

Multi-particle production & initial state correlations

Multi-particle production from a single (semi-) hard scattering, gives rise to long range ($\Delta\eta$) away side ($\Delta\phi \sim \pi$) correlation

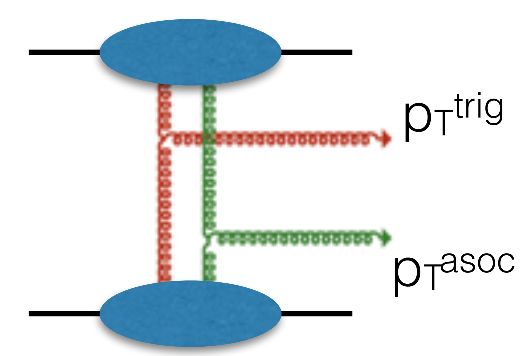


"Jet graph"



Dominant process for particle production in min. bias and low multiplicity p+p/A events

In high-multiplicity events multi parton processes become increasingly important



"Glasma graph"

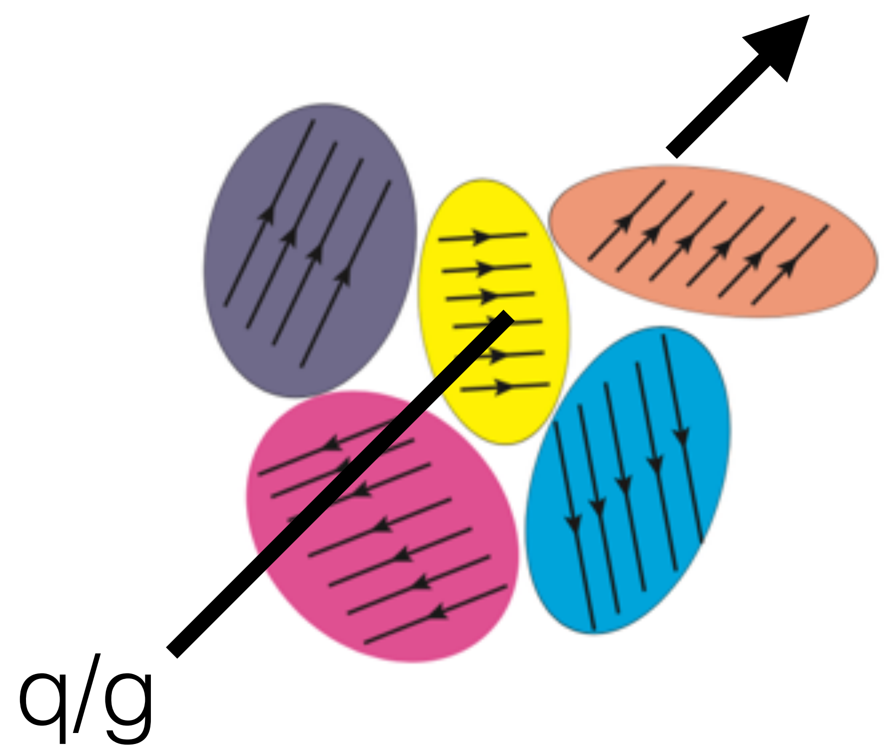
Correlation between produced particles directly reflect the correlations of gluons inside the wave function of projectile and the target

(Gelis,Lappi Venugopalan PRD 78 (2008) 054020, PRD 79 (2009) 094017; Dumitru, Gelis, McLerran,Venugopalan NPA8 10, 91 (2008); Dumitru, Jalilian-Marian PRD 81 (2010) 094015)

Multi-particle production in high-multiplicity events

Intuitive picture at small x:

Bose enhancement of small x gluons in wave function allows treatment as a classical color field



Scattering amplitude of projectile parton

$$V_x = \mathcal{P}\, e^{-ig\int dx^- A^+}$$

Distribution of scattered partons

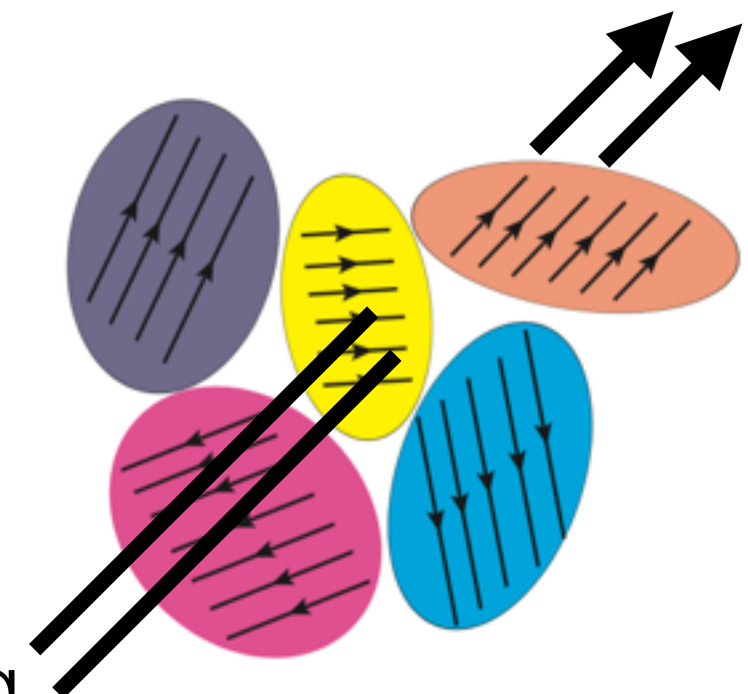
$$\frac{dN_{q/g}}{d^2\mathbf{k}_T} = \int_{\mathbf{p}_T,\mathbf{b}_T,\mathbf{r}_T} W_{q/g}(\mathbf{p}_T,\mathbf{b}_T)\, e^{-i(\mathbf{k}_T-\mathbf{p}_T)\mathbf{r}_T} \quad \mathrm{tr}_{f/a} V(\mathbf{b}_T+\mathbf{r}_T/2)V^\dagger(\mathbf{b}_T-\mathbf{r}_T/2)$$

Short-distance expansion: Each parton receives a momentum kick in the direction of the light-cone electric field $E^i(\mathbf{b}_T) = \frac{i}{g} V(\mathbf{b}_T)\partial^i V^\dagger(\mathbf{b}_T)$

Multi-particle production in high-multiplicity events

Intuitive picture at small x:

Each parton scattering off the same domain receives a kick in the direction of the chromo-electric field which leads to a correlation in azimuthal angle



$$\left\langle \frac{dN_{q/g}}{d^2\mathbf{k}_1 d^2\mathbf{k}_2} \right\rangle = \int_{\mathbf{p}_1,\mathbf{b}_1,\mathbf{r}_1}^{\mathbf{p}_2,\mathbf{b}_2,\mathbf{r}_2} W_{q/g}(\mathbf{p}_1,\mathbf{b}_1)\, e^{-i(\mathbf{k}_1-\mathbf{p}_1)\mathbf{r}_1}\, W_{q/g}(\mathbf{p}_2,\mathbf{b}_2)\, e^{-i(\mathbf{k}_2-\mathbf{p}_2)\mathbf{r}_2}$$

$$\left\langle \mathrm{tr}_{f/a} V(\mathbf{b}_1+\mathbf{r}_1/2) V^\dagger(\mathbf{b}_1-\mathbf{r}_1/2) \mathrm{tr}_{f/a} V(\mathbf{b}_2+\mathbf{r}_2/2) V^\dagger(\mathbf{b}_2-\mathbf{r}_2/2) \right\rangle$$

-> Near-side ($\Delta\phi\sim 0$) azimuthal correlation $\sim 1/(N_c^2\, Q_s^2\, S_T)$

Since the rapidity evolution is slow ($\Delta\eta_{corr}\sim 1/\alpha_s$) is long range in rapidity

(Kovner,Lublinsky PRD 83 (2011) 034017; Dumitru, Giannini NPA 933 (2014) 212-228; Dumitru, Skokov PRD 91 (2015) 7, 074006; Lappi, Schenke, SS, Venugopalan 1509.03499)

Phenomenological calculations

1 Initial state multi-particle production

Perturbative CGC calculation

Dumitru, Dusling, Gelis, Jalilian-Marian, Lappi, Venugopalan
PLB 697 (2011) 21-25

Dusling, Venugopalan
PRD 87 (2013) 5, 051502,
PRD 87 (2013) 5, 054014,
PRD 87 (2013) 9, 094034

Dusling, Tribedy, Vengopalan
PRD 93 (2016) 1 014034

Hybrid formalism

Dumitru, Giannini
NPA933 (2015) 212-228

Dumitru, McLerran, Skokov
PLB 743 (2015) 134-137

Lappi
PLB 744 (2015) 315-319

Lappi, Schenke, SS, Venugopalan
JHEP 1601 (2016) 061

McLerran, Skokov
NPA 947 (2016) 142-154

Classical Yang-Mills simulations

Schenke, SS, Venugopalan
PLB 747 (2015) 76-82

Schenke, SS, Tribedy, Venugopalan
arXiv:1607.02496

2 Hadronization

Fragmentation functions

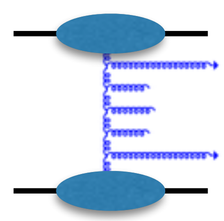
Monte-Carlo fragmentation schemes (PYTHIA HSA)

Phenomenological calculations

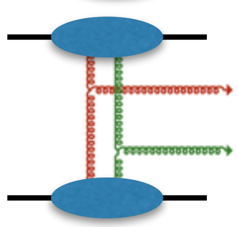
Perturbative calculation in CGC framework

(Dusling, Venugopalan PRD 87 (2013) 5, 051502, PRD 87 (2013) 5, 054014, PRD 87 (2013) 9, 094034
Dusling,Tribedy, Vengopalan PRD 93 (2016) 1 014034)

Direct computation of “Jet graph” + “Glasma graph”
in k_T factorized approximation (valid at $p_T > Q_S$)

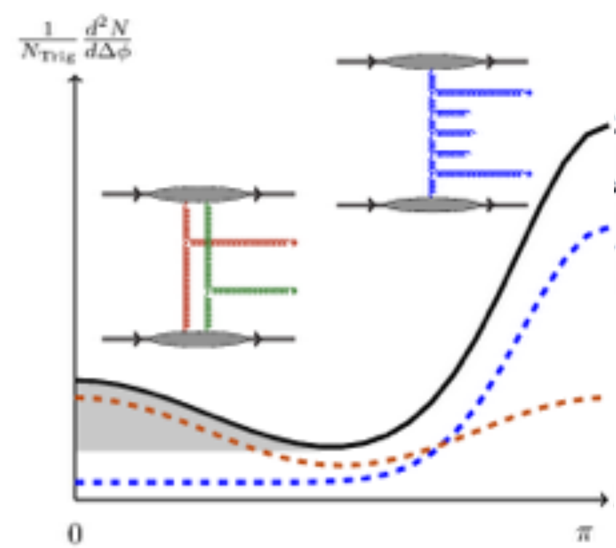


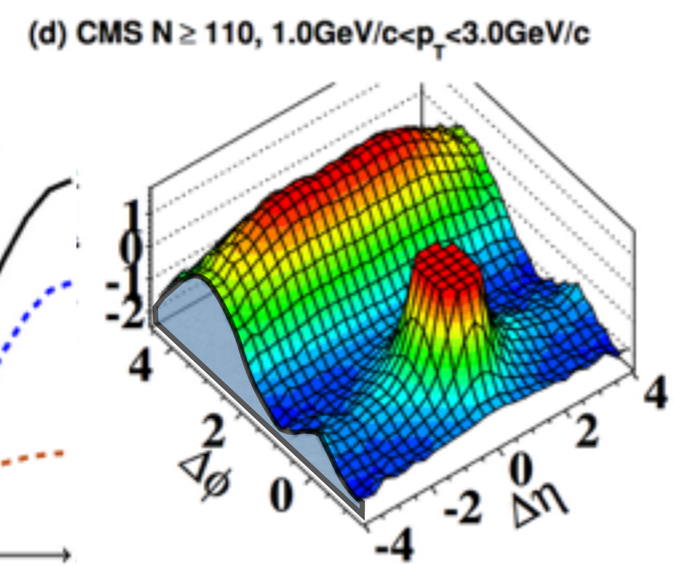
$$\frac{d^2 N^{\rm corr.}_{\rm BFKL}}{d^2\mathbf{p}_T d^2\mathbf{q}_T dy_p dy_q} = \frac{32\, N_c\, \alpha_s^2}{(2\pi)^8\, C_F}\, \frac{S_\perp}{\mathbf{p}_T^2 \mathbf{q}_T^2} \int_{\mathbf{k}_{0\perp}} \int_{\mathbf{k}_{3\perp}} \Phi_A(\mathbf{k}_{0\perp}) \Phi_B(\mathbf{k}_{3\perp})\, \mathcal{G}(\mathbf{k}_{0\perp} - \mathbf{p}_T, \mathbf{k}_{3\perp} + \mathbf{q}_T, y_p - y_q),$$



$$\frac{d^2 N^{\rm corr.}_{\rm Glasma-1}}{d^2\mathbf{p}_T d^2\mathbf{q}_T dy_p dy_q} = \frac{32 \alpha_S^2}{(2\pi)^{10} \zeta\, N_c C_F^3}\, \frac{S_\perp}{\mathbf{p}_T^2 \mathbf{q}_T^2} \int_{\mathbf{k}_T} \Phi_A^2(\mathbf{k}_T) \Phi_B(\mathbf{p}_T - \mathbf{k}_T) \Phi_B(\mathbf{q}_T - \mathbf{k}_T) \quad + \ldots$$

Glasma graphs produce long range azimuthal correlation symmetric around $\Delta\phi = \pi/2$ and gives rise to even harmonics v_2, v_4, …





CMS JHEP 1009 (2010) 091

Detailed comparison in p+p & p+Pb

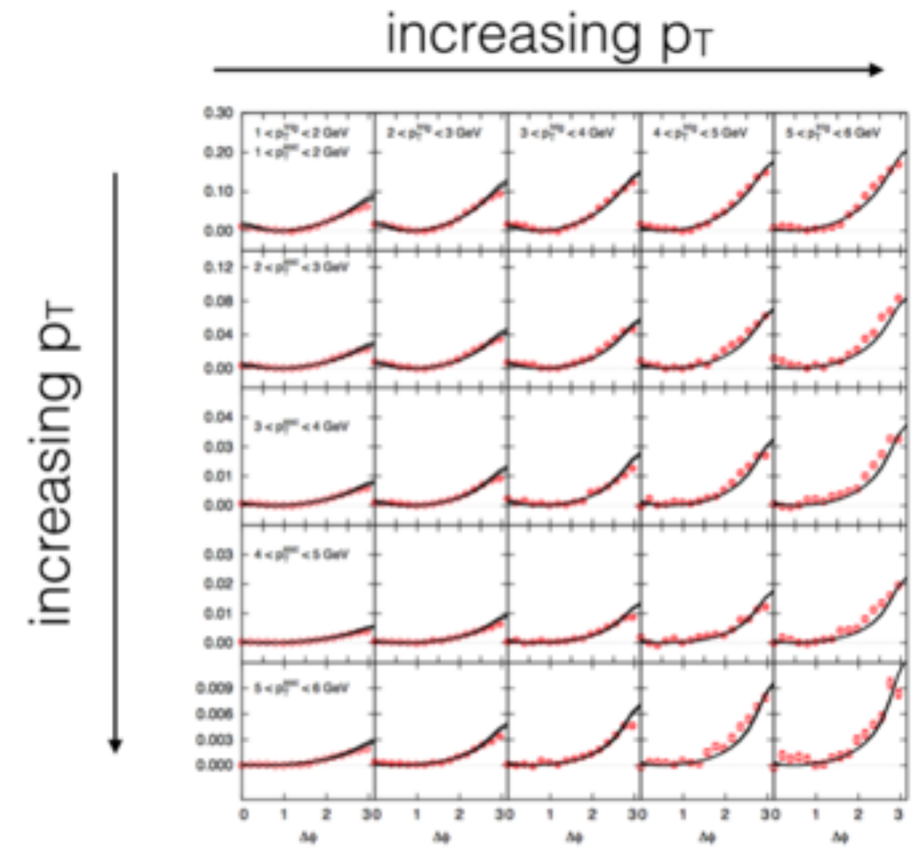
Dusling, Venugopalan PRD 87 (2013) 9, 094034

Unintegrated gluon densities constrained from DIS fits

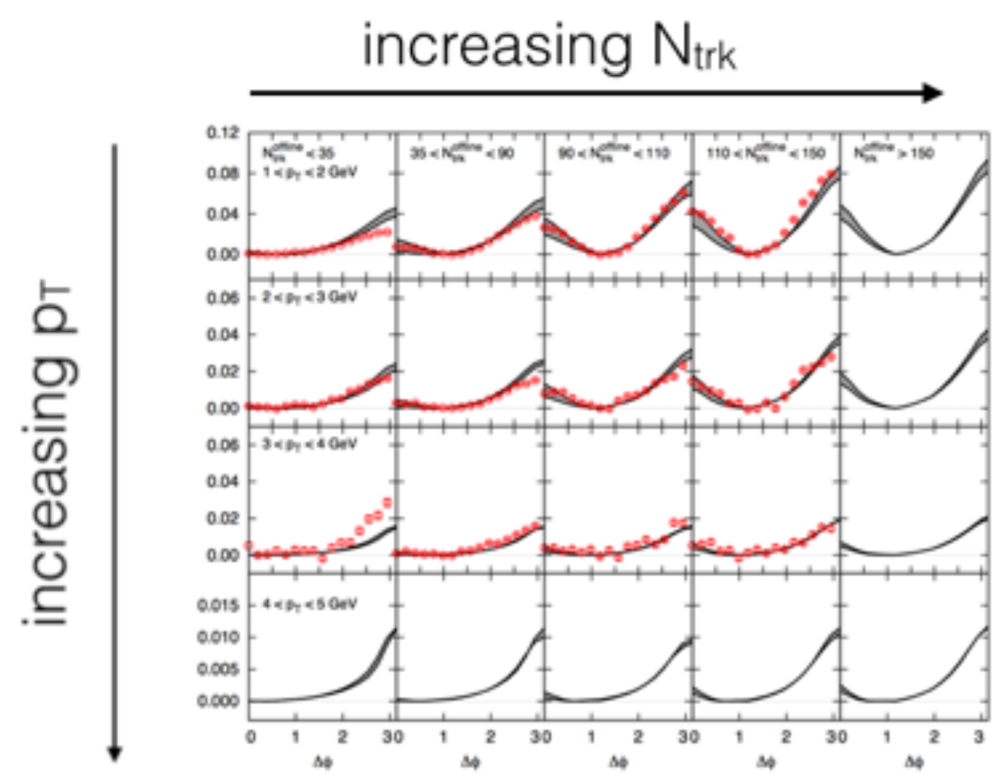
High-multiplicity events modeled by increasing Q_s

Differential comparison in p_T and N_{trk} yields good overall agreement for two-particle correlations in wide kinematic range for moment p_T>1 GeV

Challenge: Quantify theoretical uncertainties and extend range of validity of calculations to smaller momenta (p_T<Q_s)



p+p 7 TeV high mult. N_{trk}>110



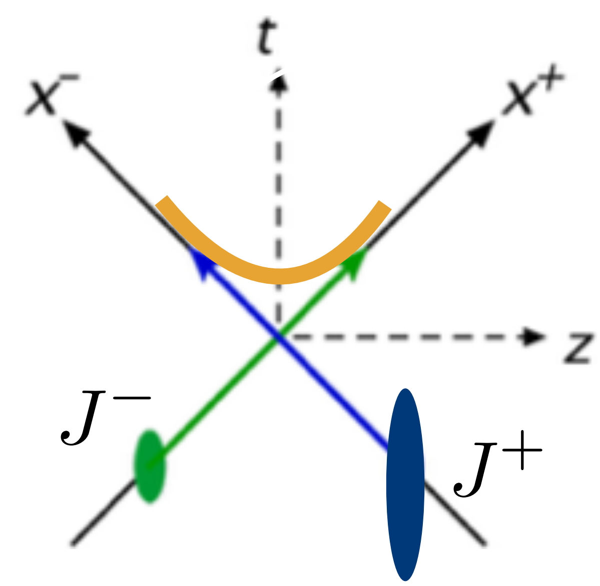
p+Pb 5.02 TeV

Phenomenological calculations

Event-by-event simulations in classical-Yang Mills theory

Describing projectile and target as color charges moving at the speed of light the properties of the initial state (τ=0) and early time dynamics (τ~#/Q_S) can be calculated by solving the classical Yang-Mills equations

$$[D_\mu, F^{\mu\nu}] = J^\nu$$



Initial state known analytically $$A^i(\mathbf{x}, \tau = 0) = \frac{i}{g}\left(V_1(\mathbf{x})\partial^i V_1^\dagger(\mathbf{x}) + V_2(\mathbf{x})\partial^i V_2^\dagger(\mathbf{x})\right)$$

early time dynamics can be computed based on real-time lattice techniques

Based on the knowledge of correlation functions of light-like Wilson V_1,V_2 lines one can event-by-event by simulations and calculate various observables

Multiplicity, event shapes, multi-particle correlations, …

Basis of IP-Glasma initial state model for A+A collisions

(Krasnitz, Venugopalan NPB557 (1999) 237, Lappi, McLerran NPA772 (2006) 200-212, Schenke,Tribedy,Venugopalan C86 (2012) 034908, Schenke,SS,Venugopalan PLB747 (2015) 76-82, …)

Phenomenological calculations

Event-by-event simulations in classical-Yang Mills theory

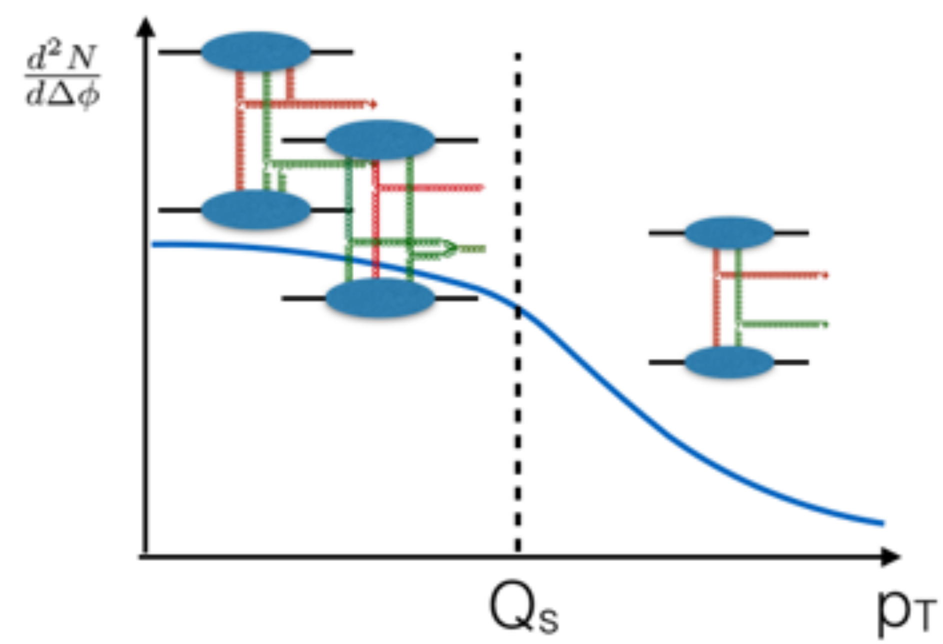
(Schenke, SS, Venugopalan PLB 747 (2015) 76-82, Schenke,SS,Tribedy,Venugopalan PRL 117 (2016) no.16, 162301)

Event-by-event simulations allow for a natural multiplicity selection as in experiments and an adequate treatment of impact parameter dependence and system geometry (p/d/He+A)

Comparison to perturbative approach:

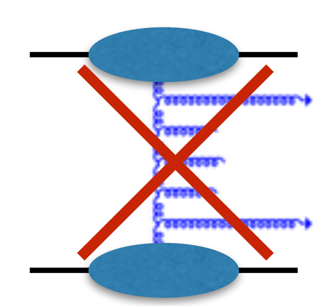
Event-by-event simulations include multi-particle production via Glasma graphs

Simulations consistently include multiple-scattering effects (important at $p_T<Q_s$), extend beyond the range of validity of perturbative calculation



Classical Yang-Mills simulations at present do not include Jet graphs

(work in progress Dusling,Tribedy,SS,Venugopalan)



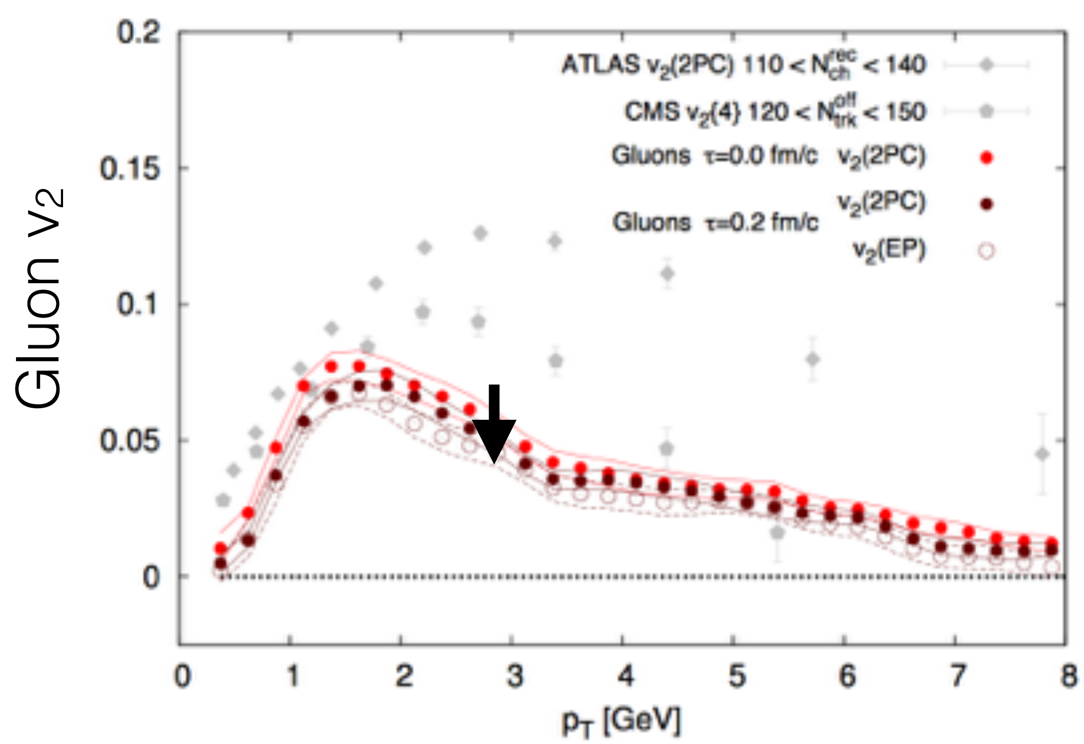
Phenomenological calculations

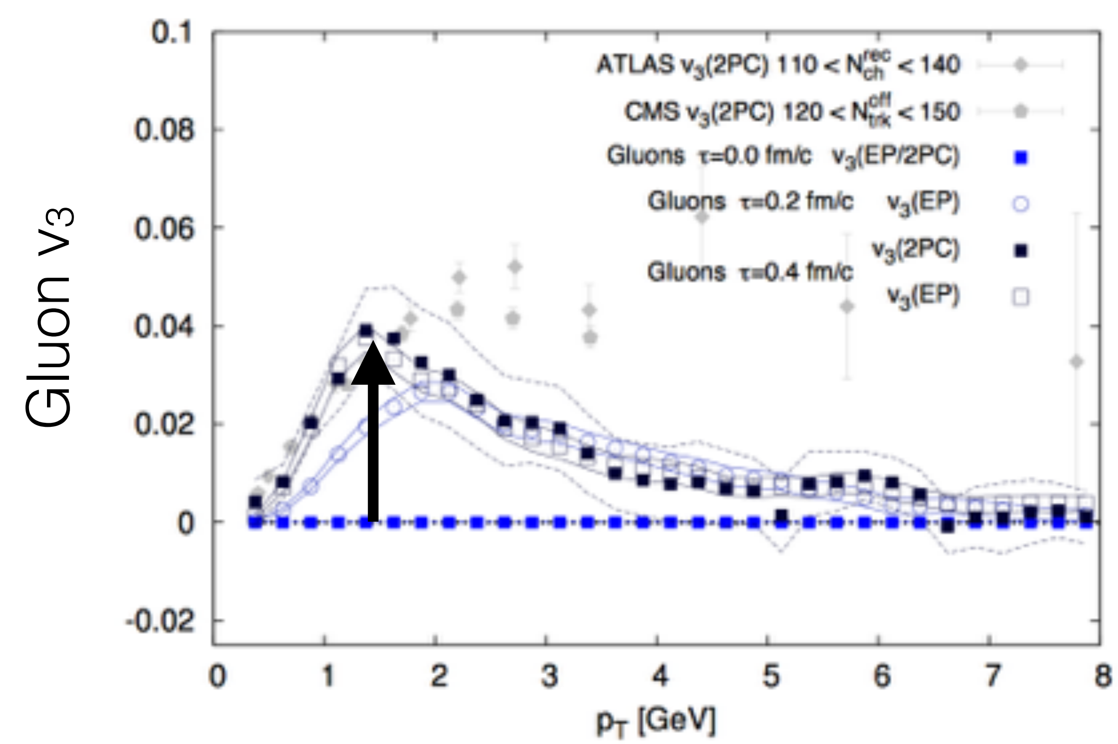
Event-by-event simulations in classical-Yang Mills theory

(Schenke, SS, Venugopalan PLB 747 (2015) 76-82, Schenke,SS,Tribedy,Venugopalan PRL 117 (2016) no.16, 162301)

Gluons are produced with a momentum space correlation already at $\tau=0^+$

-> Initially correlation function only features even harmonics $v_2, v_4, \ldots$





Including final state re-scattering via CYM evolution generates a positive v_3 on the time scale $\sim 1/Q_s$ of a single scattering

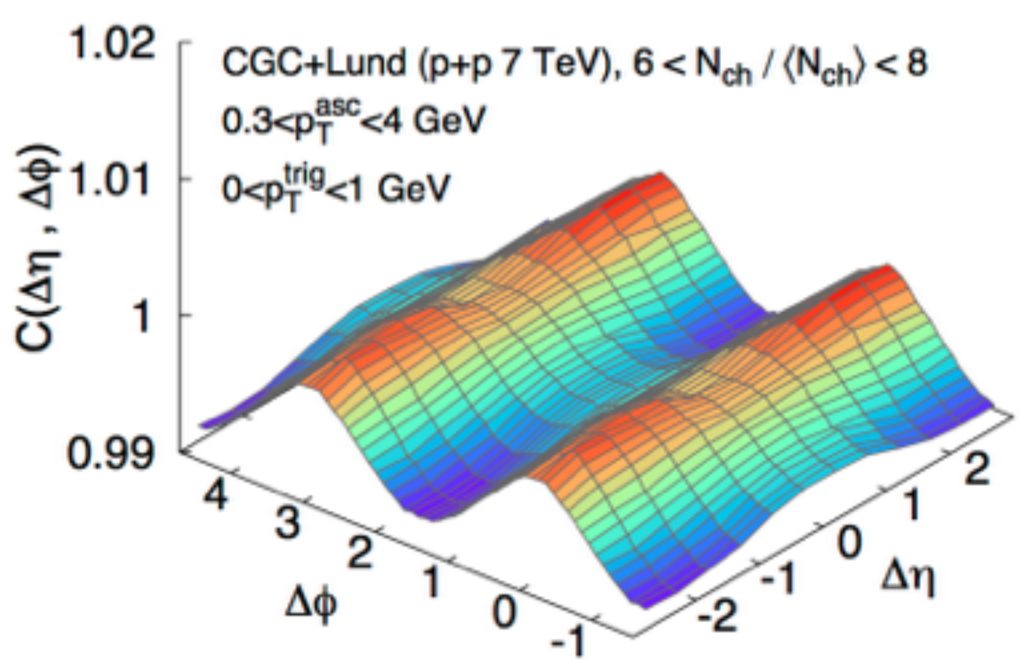
Phenomenological calculations

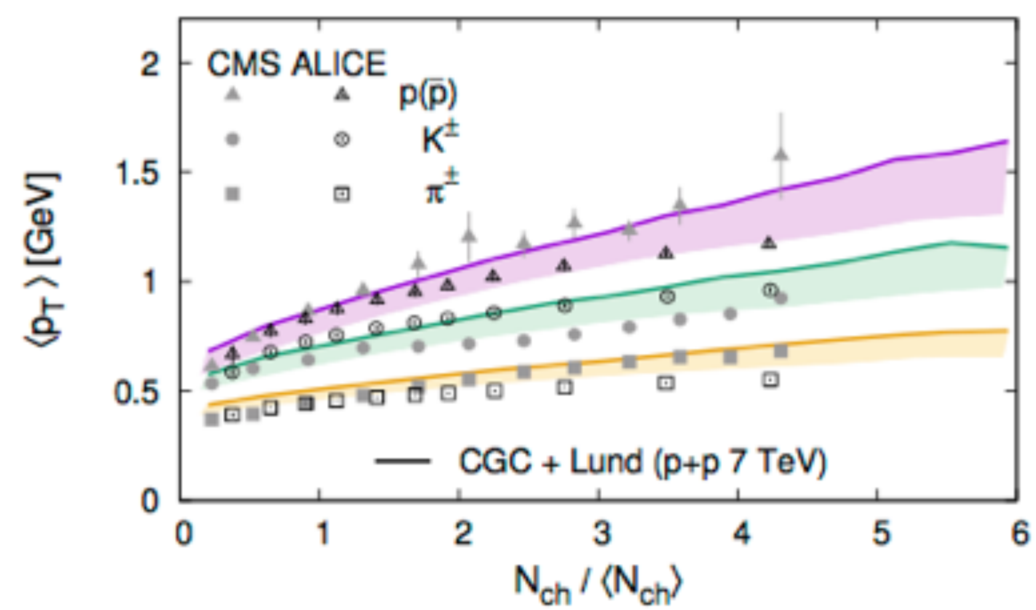
Event-by-event simulations in classical-Yang Mills theory + MC Lund string fragmentation

(Schenke,SS,Tribedy, Venugopalan PRL 117 (2016) no.16, 162301)

Extract event-by-event gluon spectra from classical Yang-Mills simulation and sample individual gluons to perform fragmentation in PYTHIA

-> Direct comparison of hadronic observables with experiment





Initial state correlations at the gluon level combined with string fragmentation naturally reproduces characteristic features of hadronic observables

Challenges & perspectives

Competing theoretical explanations for long range azimuthal correlations observed in high-multiplicity p+p/A collisions

Initial state
momentum correlations

Hydrodynamic response
to initial geometry

Simultaneous description of low p_T and high p_T data across a wide range of multiplicities remains a challenge within all presently available theoretical framework

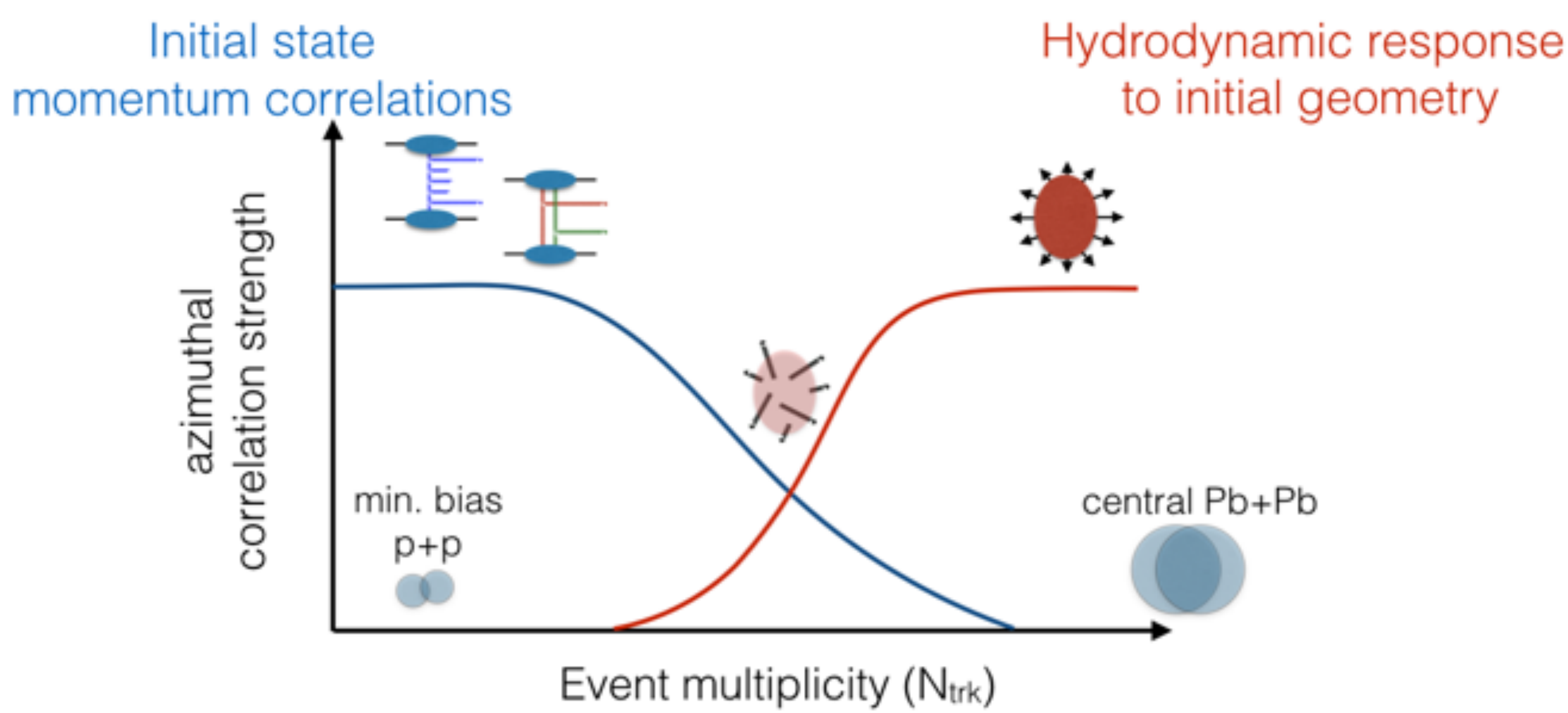
So far calculations based on dominance of initial state or final state effects

Challenges: Develop theoretical framework including initial state & final state effects

Identify observables which can unambiguously distinguish between different regimes

Challenges & perspectives

Qualitative picture of long range azimuthal correlations



Understanding the transition from initial state to final state dominance closely related to understanding formation of QGP in A+A collision

Even though some of these questions will have to be resolved in Heavy-Ion community there are interesting relations to EIC physics

intrinsic multi-parton correlations

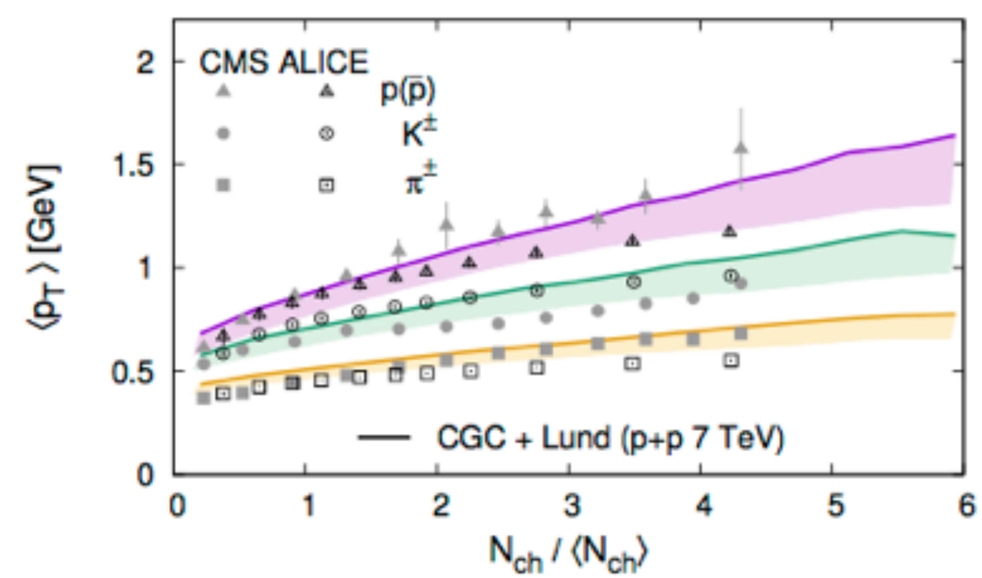
event-by-event fluctuations of proton geometry

Backup

<p_T> & <v_2> mass ordering

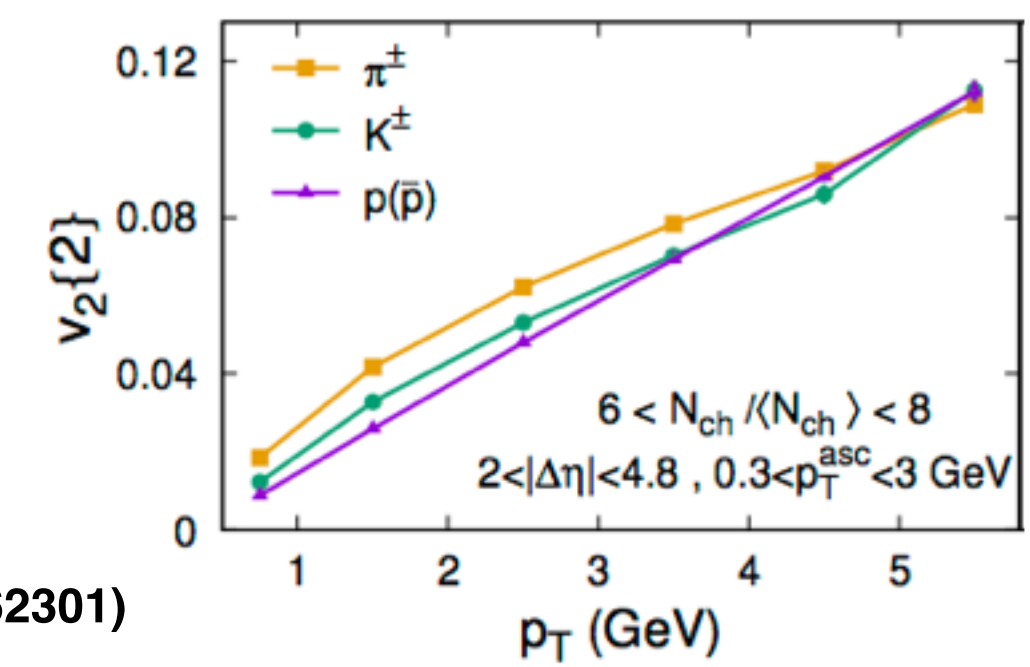
p+p 7 TeV

Increase of <p_T> with N_{ch} due to increase of Q_s already present at gluon level



String fragmentation naturally leads to observed "mass splitting"

Correlations at the gluon level due to initial state production (Glasma graphs)

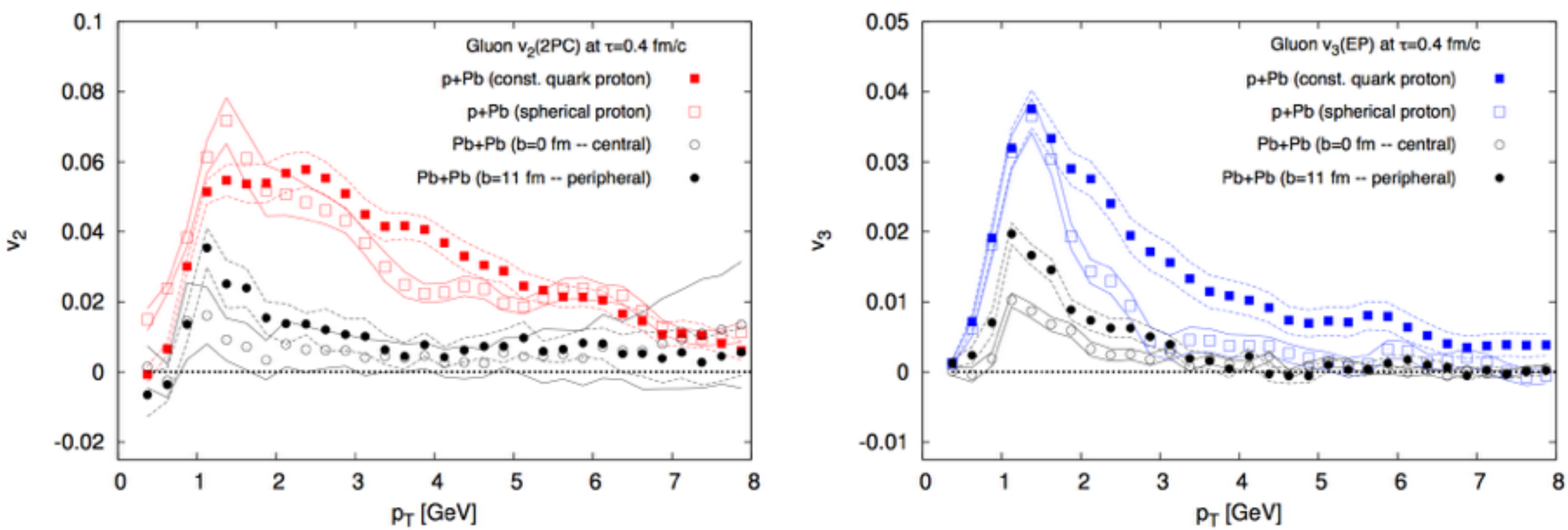


String fragmentation naturally leads to "mass splitting"

(Schenke,SS,Tribedy, Venugopalan PRL 117 (2016) no.16, 162301)

-> Mass ordering property of identified particle correlations sensitive to hadronization mechanism rather than origin of correlation

Dependence on event geometry & system size



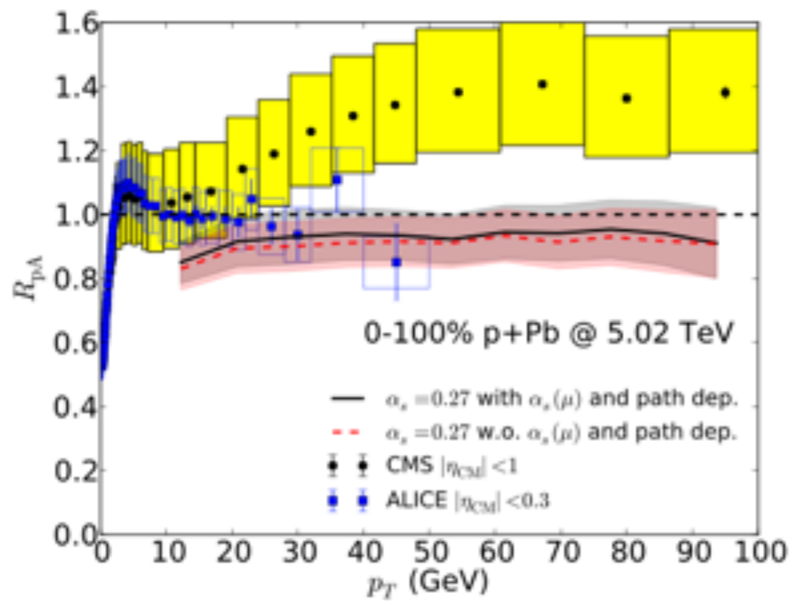
(Schenke, Schlichting, Venugopalan PLB 747 (2015) 76-82)

Event-geometry irrelevant for initial state correlation in p+A

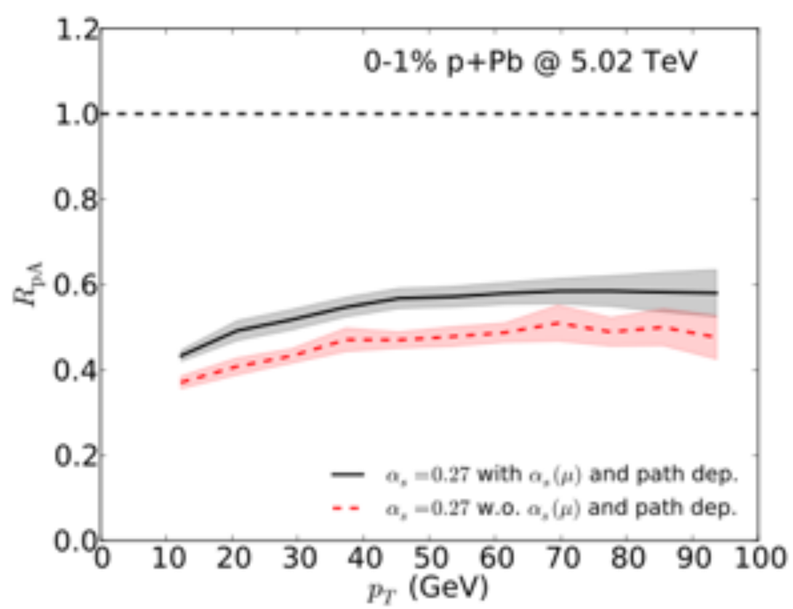
Substantially smaller effect even in rather peripheral A+A

Jet-Quenching in p+A?

Jets in the pA medium?
Here, charged hadrons



- Situation in min. bias pA clearly sensitive to the value of α_s
- Some possibility of suppression @~10-20 GeV, but data mostly 1



- A large(r) effect in central collisions
- Enhanced sensitivity to physical conditions and model characteristics (medium size and granularity)
- Much more to do: y, jet R_{pA}...
- A clear manifestation of the medium in pA collisions

(C.Gale — Quark Matter 2015)

Phenomenological calculations

Event-by-event simulations in classical-Yang Mills theory + MC Lund string fragmentation

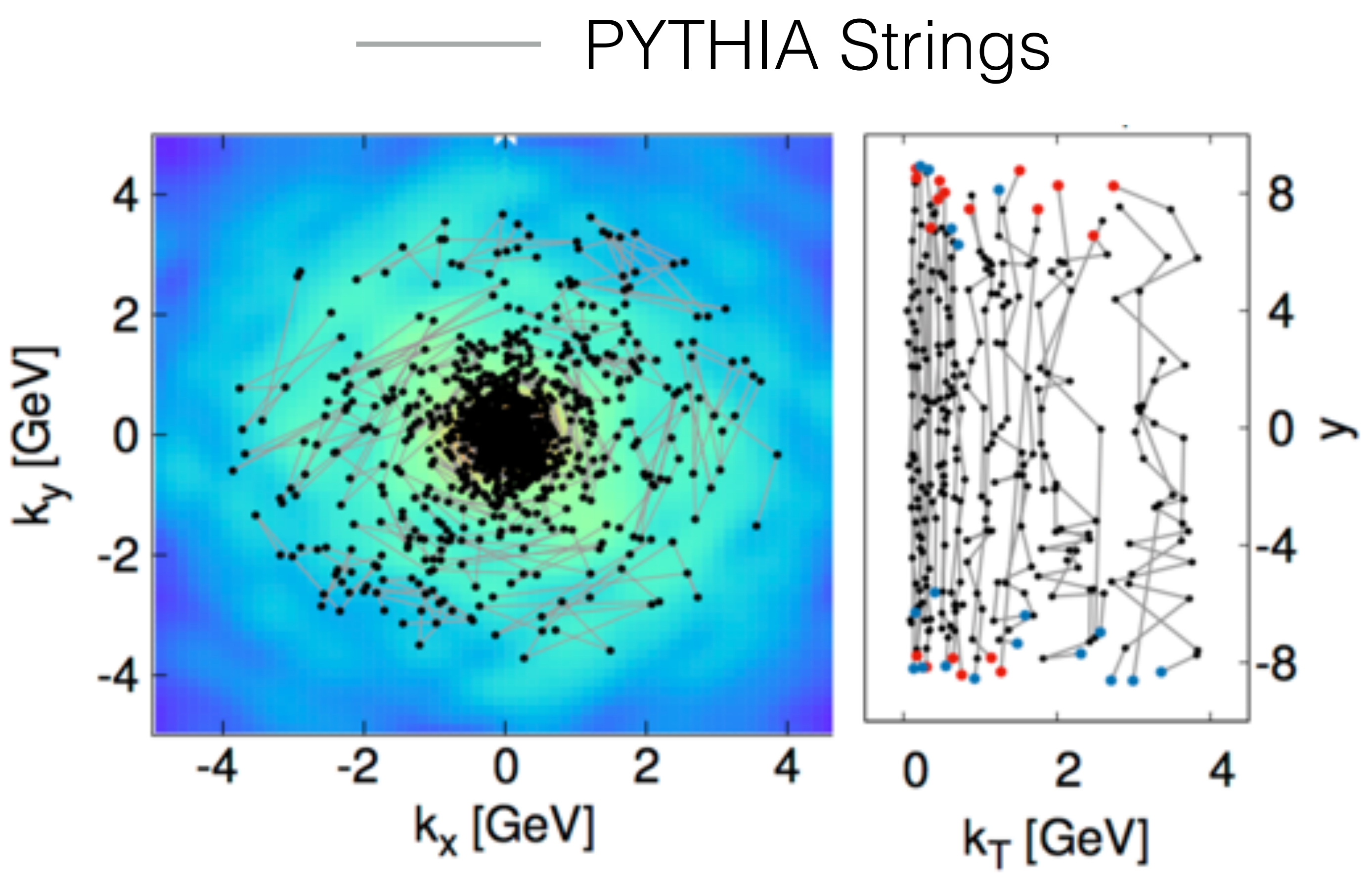
(Schenke,SS,Tribedy, Venugopalan PRL 117 (2016) no.16, 162301)

Extract event-by-event gluon spectra from classical Yang-Mills simulation

-> includes initial state correlations

Sample individual gluons according to dN_g/d^2k, group into strings and perform Lund string fragmentation implemented in PYTHIA

-> "CGC+Lund event generator"



Can follow experimental analysis to compute hadronic observables

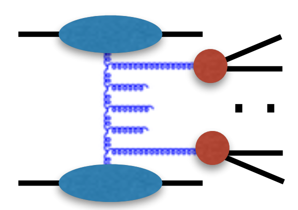
Collectivity

Collectivity from initial state?

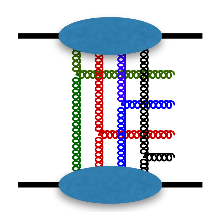
Experiments observe similar features in multi-particle correlations (n>2)

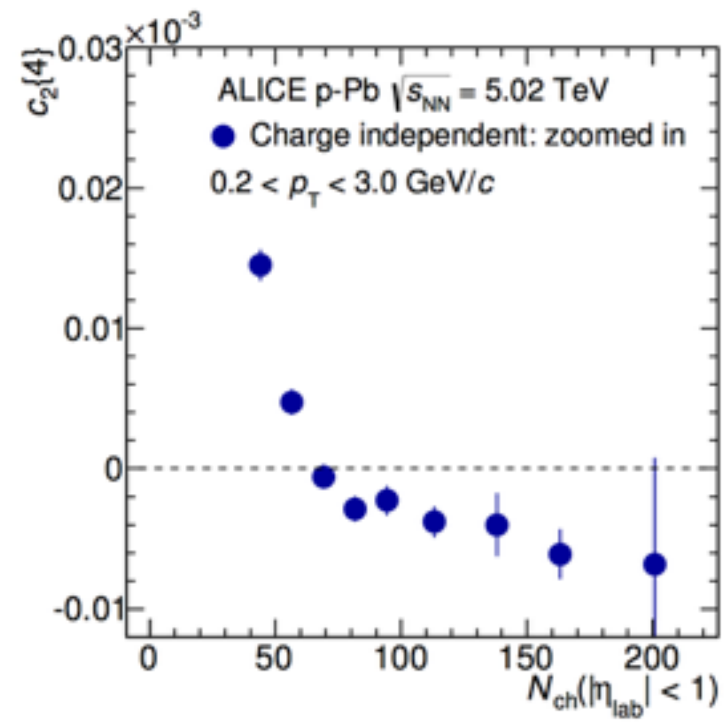
Difficult to compute because no $\Delta\eta$ gap and low p_T

-> many possible contributions



Initial state framework naturally extends to higher order correlations





ALICE PRC 90, 054901 (2014)

Sensitive to higher order correlations of gluons inside the projectile and target wave-functions

Qualitative results:

(Dumitru,McLerran,Skokov B743 (2015) 134-137)

perturbative result

$$c_2\{4\} = -\frac{1}{N_D^3}\left(\mathcal{A}^4 - \frac{1}{4(N_c^2-1)^3}\right)$$

non-linear/non-Gaussian effects

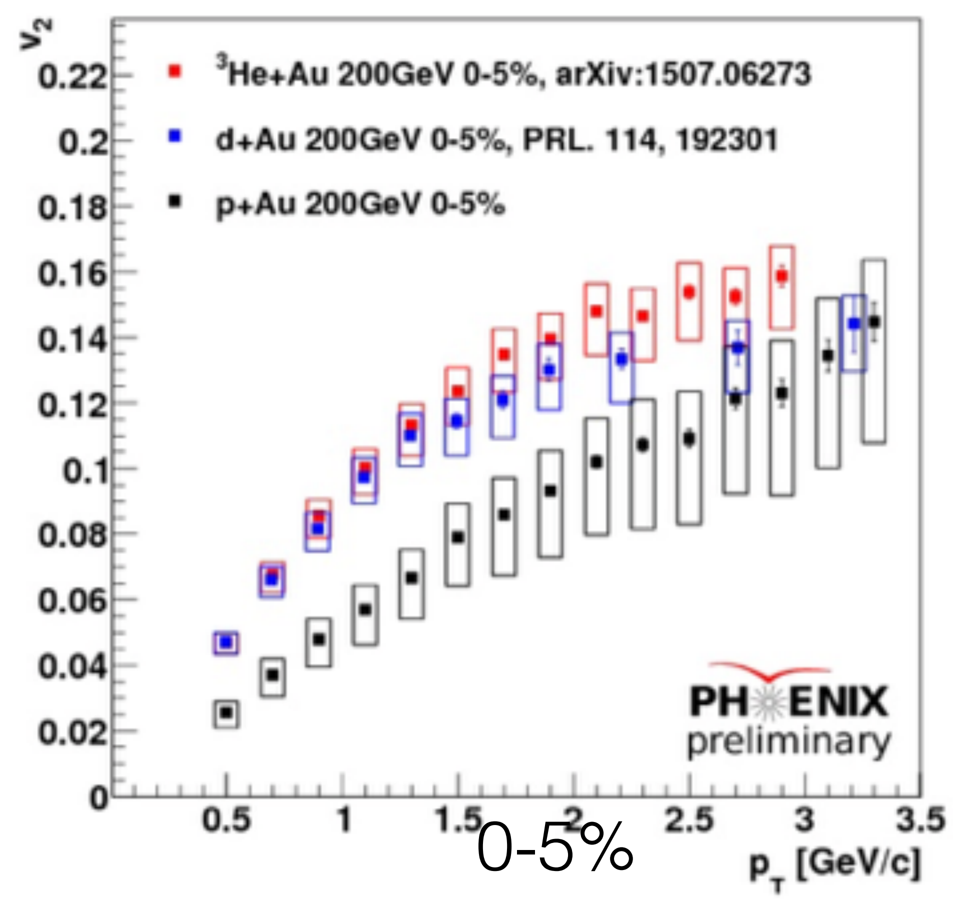
p/d/He3 collisions at RHIC

Striking observation of hierarchy
in p/d/He3+A collisions observed

v_2(p+Au) < v_2(d+Au) ≤ v_2 (He3+Au)

Extracted from event-plane method

Back-to-back mini jets?



Theoretical description requires to properly
include impact parameter dependence

-> Event-by-event Yang-Mills simulations +Jets + Hadronization

(work in progress Dusling,SS,Tribedy,Venugopalan)